J. Phys. G: Nucl. Part. Phys. **28** (2002) 2885–2891 PII: S0954-3899(02)53283-7

RESEARCH NOTES FROM COLLABORATIONS

Diffraction at RHIC

A Bravar[1], W Guryn[1], S R Klein[2], D Milstead[3] and B Surrow[1]

[1] Brookhaven National Laboratory, Upton, NY, 11973, USA
[2] Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA
[3] University of Liverpool, Liverpool, L69 3BX, UK

Received 11 September 2002
Published 17 October 2002
Online at stacks.iop.org/JPhysG/28/2885

Abstract

The relativistic heavy ion collider (RHIC) offers many opportunities to study diffraction in pp, pA and AA collisions. Because both proton beams can be polarized, RHIC offers the unique possibility of studying polarization effects in diffraction. We will introduce diffraction at RHIC and present three compelling physics topics: hard diffraction with polarized beams, identification of exotic mesons (non-$q\bar{q}$ states) in double-Pomeron collisions and using diffraction to measure the low-x gluon density in pA collisions, testing models of gluon saturation and the coloured glass condensate. This note developed from discussion at a workshop on 'Diffraction and Glueball Production at RHIC' at Brookhaven National Laboratory, 17–18 May 2002.

1. Introduction

Diffractive events occur via the exchange of colour singlet objects, Pomerons, with the same quantum numbers as the vacuum ($J^{PC} = 0^{++}$) [1]. They are characterized by final states which include rapidity gaps, regions of phase space containing no final state particles. Examples are pp elastic scattering, photoproduction of vector mesons, and diffractive $W^{\pm}$ production. Typical hadronic interactions, in contrast, involve the exchange of coloured particles, where the probability of finding a particle-free region with a width of Δy units of rapidity is exponentially suppressed as $\exp(-\Delta y\, \mathrm{d}N/\mathrm{d}y)$, where $\mathrm{d}N/\mathrm{d}y$ is the mean number of particles per unit rapidity. Meson exchange can also produce rapidity gaps. However, the meson exchange contribution drops with increasing collision energy, while the Pomeron exchange cross section increases slightly. So, at high (relativistic heavy ion collider (RHIC)) energies, processes with rapidity gaps are expected to be dominated by Pomeron exchange.

Despite 40 years of studying diffraction, many questions remain. Soft (low energy) diffraction is usually characterized in terms of the optical model as represented by the absorptive part of the cross section, and via a Regge trajectory. The optical model can describe phenomena such as elastic scattering and vector meson photoproduction, but does very poorly with hard reactions such as $W^{\pm}$ and jet production. These higher momentum-transfer reactions may be explainable within perturbative QCD as via Pomeron exchange [2],

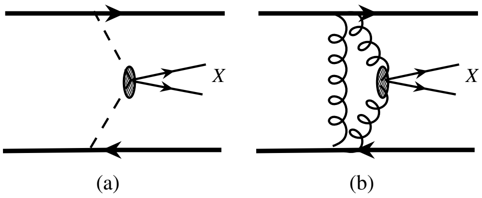

Figure 1. The main diagrams for diffractive meson production. (a) Double Pomeron fusion and (b) the gluon triangle.

where the Pomeron is represented as a gluon ladder (two gluons connected by additional gluon and quark loop 'rungs'). These models are moderately successful in explaining many hard diffraction phenomena.

Despite these successes, many questions and controversies remain. In pp collisions, it is still unclear whether diffractive jet production can be explained as due to the collisions of two Pomerons. Can the Pomeron flux from a relativistic proton be described in terms of a Pomeron distribution, akin to the usual parton distributions? Another example involves photoproduction. At HERA, the J/ψ and ψ' cross sections rise sharply with energy [3], in contrast to the expected slow energy dependence of the Pomeron exchange model. This has been argued to be a threshold effect, or due to a hard component of the Pomeron.

The nature of the Pomeron is also debated. In the simplest models, it is almost entirely gluonic. However, the observation of diffractive deep inelastic scattering [4] and diffractive $W^{\pm}$ production in $p\bar{p}$ collisions [5] both require a significant quark component. The role of the 3-gluon triangle (figure 1(b)) is also debated. It is also difficult to explain hard and soft diffraction within a single theory [6]; some papers argue that they are two distinct phenomena [7]. For the soft Pomeron, this is little understanding of how diffraction (i.e. the absorptive part of the cross section) meshes with coloured QCD reactions.

RHIC can bring significant new data to bear on many of these questions. One key feature of RHIC is its polarized proton beams, allowing for the first time studies of polarized hard diffraction up to centre-of-mass energies of 500 GeV. As the first high energy pp collider, RHIC can also look for differences between pp and $p\bar{p}$.

These studies will complement studies of pp elastic scattering by the $pp2pp$ collaboration [8]. The $pp2pp$ collaboration will measure single and double spin asymmetries in elastic scattering, and so probe the spin structure of the Pomeron at very soft momentum scales.

Diffraction is also a tool to study meson spectroscopy. Double-diffractive (two rapidity gaps) central production of mesons has been studied extensively at the CERN SPS[4]. The experiments found that invariant mass spectra changed drastically when the protons were 'kicked' in opposite directions, compared to when the protons went in the same direction. This 'p_T filter' is still poorly understood, but is clearly important for both meson spectroscopy and for studies of diffraction. RHIC studies of the spin dependence of the p_T filter could yield qualitatively new information.

Events with rapidity gaps can also be a place to search for new physics [10]. The new physics can occur via either double-Pomeron or two-photon interactions. The two event classes look similar, except that in two-photon interactions, the outgoing protons have a smaller average p_T; the classes may be statistically separated on this basis [11].

[4] CERN experiments WA-76, WA-91 and WA-102 have many papers showing how double-Pomeron interactions are an excellent place to search for exotic mesons (see [9]).

Diffractive pA collisions can be used to study the nucleus. If the Pomeron is made up of two gluons, then the Pomeron should exhibit nuclear shadowing (the EMC effect), with a magnitude roughly the square of the size of gluon shadowing [12].

These diffractive measurements are important in understanding cosmic ray air showers. Forward interactions dominate the energy flow in high energy collisions, and measurements in this region are critical in modelling air showers from very high energy cosmic rays.

Diffraction usually requires that the interacting protons remain intact. Dedicated forward detectors called Roman pots are commonly used to observe the outgoing protons. Roman pots detect protons travelling inside the beam pipe of the accelerator, making it possible to measure very small scattering angles. Since the Roman pots are usually placed past the accelerator magnets, they can act as spectrometers, measuring the kinematics of the scattered protons. At RHIC, diffraction could be studied by adding two Roman pot systems to a central detector. Because of the angular sensitivity of the p_T filter and all spin measurements, pots with full azimuthal acceptance are very desirable.

This physics was discussed at a workshop on 'Diffraction and Glueball Searches at RHIC', at Brookhaven National Laboratory, 17–18 May 2002 [13]. The workshop found ample physics justification to install a Roman pot system around one of the existing detectors. This write-up will now present three core topics discussed at the workshop: meson spectroscopy, hard diffraction in pp and diffraction in pA.

2. Meson production in soft pp diffraction

Mesons can be produced diffractively via Pomeron–Pomeron fusion, $pp \to ppPP \to ppX$, figure 1. Pomeron–meson and meson–meson fusions are also possible. At lower energies, the meson contributions are important; at RHIC, they should be small. Because Pomerons are believed to have a largely gluonic content, double-Pomeron collisions may be a good channel to search for glueballs.

Double-Pomeron production of mesons has been studied extensively by experiments WA 76/91/102 at the CERN SPS (see footnote 4). These experiments made a remarkable discovery: the character of the produced mesons depended strongly on the direction of the momentum transfer from the protons. When the transverse momentum transfers pointed in the same direction, one K^+K^- (for example) invariant mass spectrum was obtained, showing mostly conventional $q\bar{q}$ mesons. When the transverse momenta pointed in opposing directions, the K^+K^- spectrum was very different, with many suspected 'exotic' (non-$q\bar{q}$) states appearing clearly.

The difference can be seen by selecting events on the basis of $\mathrm{d}p_T$, the p_T difference between the two momentum transfers. Figure 2 shows two examples of the spectral changes in different $\mathrm{d}P_T$ bins. Conventional mesons are prominent at high $\mathrm{d}P_T$, while at low $\mathrm{d}P_T$, 'unconventional' mesons appear clearly. Partial wave analyses were used to confirm the spin/parity assignments. Similar spectral changes have been observed for many other channels, and the statistical significance of the effect is unassailable.

Many theoretical interpretations have been given for this effect. It may be evident that the Pomeron is a vector particle, or at least acts as a non-conserved vector current [15], in contrast to the expected spin-0 behavior. It has also been cited as evidence for a QCD scale anomaly [16], and for the existence of instantons [17]. The p_T filter could also be due to a large contribution from the gluon triangle diagram, figure 1(b). Alternately, it may be that Reggeon–Reggeon (meson–meson) and meson–Pomeron interactions are still important at SPS energies.

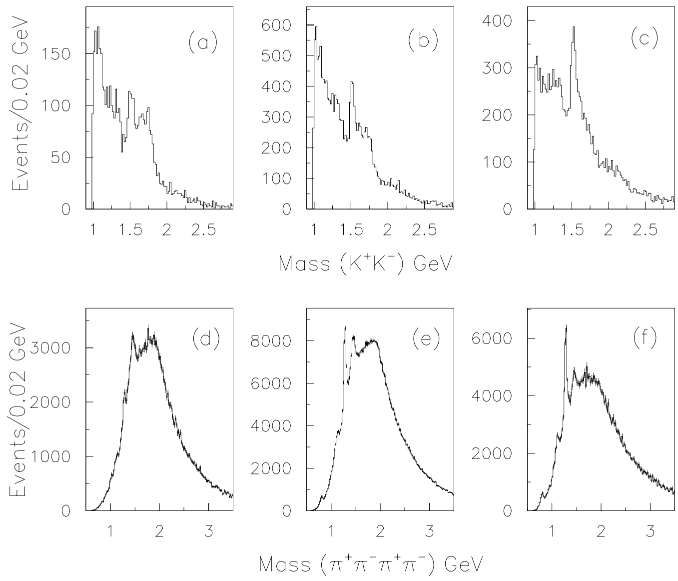

Figure 2. Invariant mass spectra for K^+K^- final states for (a) dP_T < 0.2 GeV/c, (b) 0.2 GeV/c dP_T < 0.5 GeV/c and (c) dP_T < 0.5 GeV/c. The $f_2'(1525)$, a conventional $q\bar{q}$ meson is most prominent in (c), while the $f_J(1710)$, a suspected glueball, is clearest in (a). The $\pi^+\pi^-\pi^+\pi^-$ invariant mass for (d) dP_T < 0.2 GeV/c, (e) 0.2 GeV/c dP_T < 0.5 GeV/c, (f) dP_T < 0.5 GeV/c. The conventional $f_1(1285)$ is strong in (f), but much weaker at lower dP_T, while the $f_0(1500)$ and $f_2(1930)$ are clearest at lower dP_T. This figure is from [14].

RHIC should be able to shed much light on this effect. If the p_T filter effect is due to meson exchange, then it should be much reduced at RHIC. If the Pomeron acts as a vector particle, then it is likely to display spin effects which should be visible in polarized collisions.

The cross section for double-diffractive interactions at RHIC is about 100–200 μb [18], corresponding to an interaction rate of 20 kHz, even at a centre-of-mass energy of 200 GeV and a luminosity of 10^{31} cm^{-2} s^{-1}. RHIC will produce hundreds of millions of diffractive final states in a one month run, and any rate limitation is likely to be in the detector or trigger. The production rates are very high even for rather specific final states.

3. Hard *pp* diffraction

Precision measurements of hard diffraction in *ep* and $p\bar{p}$ scattering at the HERA and the Tevatron, respectively, raise many questions about factorization and the universality of the hard Pomeron. Measurements of the diffractive structure function $F_2^{D(3)}$ [19] at HERA and associated studies of the diffractive-induced hadronic final state [20] imply a universal Pomeron composed predominantly of gluons. However, efforts to apply the next-to-leading-order QCD fits from *ep* data to jet production in $p\bar{p}$ scattering have not been entirely successful.

The structure of the Pomeron can be measured in terms of β, the fraction of the total Pomeron momentum carried by the interacting parton. The β dependence of the diffractive structure function F_{JJ}^D, as derived from jet measurements at CDF [21], is shown in figure 3 for a given region of ξ, the fraction of the proton momentum carried by the Pomeron. A comparison is made with parametrizations of the diffractive structure function measured at HERA. The β dependence is similar although the overall normalization is inconsistent between the two scattering environments. Possible reasons for this include the need for a modified Pomeron

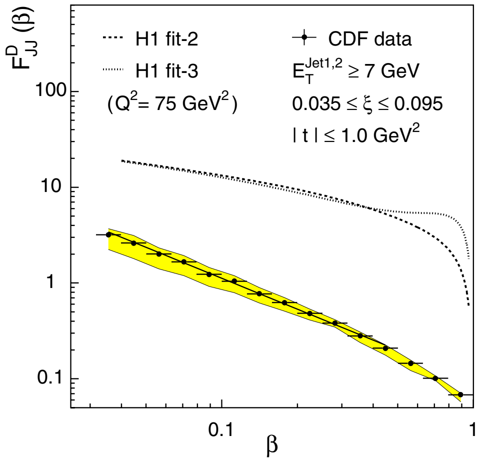

Figure 3. The diffractive structure function as a function of β, the parton momentum fraction in the Pomeron, derived from dijet production at the Tevatron compared to next-to-leading-order QCD fits from *ep* scattering at HERA. This figure is from [21]; further detail is given there.

flux at Tevatron energies owing to unitarity constraints or poorly understood gap-destroying multiple interactions present in hadronic collisions.

The study of pp scattering at RHIC can extend this field. With centre-of-mass energies up to several hundred GeV, RHIC covers a kinematic region of diffractive scattering which overlaps with HERA and the Tevatron. If Roman pot detectors were installed around one of the RHIC experiments then proton tagging would allow the study of the t dependence of the diffractive exchange. A better understanding of proton dissociation would help reduce one of the dominant systematic errors in diffraction measurements.

Further, measurements of single and double spin asymmetries will probe the spin structure of the hard Pomeron from a polarized proton. The cross sections for most diffractive processes in $p\bar{p}$ collisions are usually a small percentage (typically around 1%) of the cross section of the corresponding non-diffractive final state.

Nothing is known about the spin sensitivity of this production. Non-diffractive $W^{\pm}$, Z^0 and jet production comes largely from $q\bar{q}$ annihilation and is expected to show significant polarization asymmetries [22]; diffraction might show similar asymmetries. However, if diffraction is mediated by spin-0 Pomerons, then, to lowest order, no asymmetry is expected. At lower energies, there is some evidence that diffractive reactions may be sensitive to spin [23]. Either case would be very interesting.

In addition to measurements sensitive to the hard scales of the scattering such as jet production, the RHIC detectors can track particles down to low p_T in high-multiplicity events; these abilities will allow for high-quality measurements of particle multiplicities. Studies of multiplicity fluctuations have been used in the past to study the gluonic nature of the Pomeron [24].

The rates for hard diffractive events may be scaled from the rates for corresponding hard non-diffractive events. Here, we give the rates for a one month (10^6 s) pp run at the maximum 500 GeV centre-of-mass energy, with an assumed luminosity of 10^{32} cm^{-2} s^{-1}. The D0 collaboration finds that the rate of diffractive to non-diffractive jet events is $1.07 \pm 0.10^{+0.25}_{-0.13}\%$ [25]. Assuming that this ratio holds, RHIC will produce about two million diffractive events per year containing a jet with pseudorapidity $|\eta| < 1$ and transverse energy $E_T > 30$ GeV.[5]

[5] These rates are scaled from the numbers given in [26].

The CDF collaboration finds that diffractive $W^{\pm}$ production is $1.15 \pm 0.55\%$ of non-diffractive $W^{\pm}$ production [27]. With this ratio, each year RHIC will also produce 700 diffractive $W^+ \to e^+\nu$, 20 $W^- \to e^-$ and 4 $Z^0 \to e^+e^-$, with lepton rapidity $|\eta| < 1$.[6] The jet rates are very high, allowing for precision studies of single and double spin asymmetries and the like. Even diffractive vector boson production should be clearly visible.

4. Diffraction with heavy ions

The pA programme at RHIC enables the first studies of high energy diffraction with large and varying target sizes to take place.

Diffraction in pA collisions can be an important probe of the gluon density of heavy nuclei at low-x, where gluon densities are expected to be very high, and, even with shadowing, may saturate the available phase space [12]. In this regime, it may be possible to describe the gluons as a classical field, and new effects, such as a coloured glass condensate may be observed [29].

Diffractive processes are sensitive to the total absorptive content of the nucleus, and, through that, to the gluon content of the medium. Several specific processes have been proposed to study the gluon density at small x. For example, one could compare the rate of forward jet production in pA to that in pp to study nuclear modifications of the gluon distribution.

The t dependence of the diffractive exchange depends critically on the target size. The t and A variation of diffractive cross sections could be used to infer the relative contributions of soft and hard diffraction and their variation with A.

The breakdown in universality of the picture of the partonic Pomeron developed in deep inelastic ep scattering could be probed as a function of A. Using pp scattering as a baseline, A-dependent deviations of multi-jet production and multiplicity fluctuations from the simple partonic picture could be studied. This should be sensitive to low-x gluon shadowing and gap-destroying multiple interactions.

These studies complement the existing RHIC programme for diffraction in AA, in the form of ultra-peripheral photon–Pomeron and two-photon interactions [30]. The cross sections for photon–Pomeron fusion into vector mesons are very large [31], and ρ^0 production is observed at the predicted level [32]. Ultra-peripheral collisions may be used to study nuclear shadowing; production of both open heavy quarks [33] and quarkonium [34] is sensitive to the gluon distribution in heavy nuclei.

5. Conclusions

With its polarized beams, high luminosity and high-quality detectors, RHIC is capable of making significant contributions to our understanding of diffraction, in the areas of meson spectroscopy, hard diffraction and the low-x gluon distributions in nuclei. Much of this physics depends on measurements of the outgoing scattered protons. The proton kinematics could be determined by adding Roman pot systems upstream and downstream of a central detector at RHIC. We thank Andrew Kirk for giving permission to use figure 2. This work was supported by the US Department of Energy under Contract No DE-AC-03076SF00098.

[6] These rates are from [28] and include appropriate lepton angular distributions. This preprint assumed considerably higher luminosity and running time than we do; the rates have been scaled down.

References

[1] Barone V and Predazzi E 2002 *High-Energy Particle Diffraction* (Berlin: Springer)
[2] Forshaw J R and Ross D A 1997 *Quantum Chromodynamics and the Pomeron* (Cambridge: Cambridge University Press)
[3] Adloff C *et al* (H1 Collaboration) 1998 *Phys. Lett.* B **421** 385
Breitweg J *et al* 1997 *Z. Phys.* C **75** 215
[4] Ahmed T *et al* (H1 Collaboration) 1995 *Phys. Lett.* B **348** 681
Derrick M *et al* (ZEUS Collaboration) 1995 *Z. Phys.* C **68** 569
[5] Abe F *et al* (CDF Collaboration) 1997 *Phys. Rev. Lett.* **78** 2698
[6] Donnachie A and Landshoff P V 2002 *Phys. Lett.* B **533** 277
[7] Donnachie A and Landshoff P V 2001 *Phys. Lett.* B **518** 63
[8] Guryn W 2000 *Nucl. Phys.* A **663** 1115
[9] See Barberis D *et al* 2001 *Phys. Lett.* B **507** 14
Barberis D *et al* 2000 *Phys. Lett.* B **488** 225
Barberis D *et al* 2000 *Phys. Lett.* B **484** 198 and previous works
[10] Bjorken J D 1993 *Phys. Rev.* D **47** 101
[11] Piotrzkowski K 2001 *Phys. Rev.* D **63** 071502
[12] Dumitru A and Jalilian-Marian J 2002 *Phys. Rev. Lett.* **89** 022301
[13] See webpage http://www.star.bnl.gov/STAR/glueworkshop
[14] Kirk A 1998 *Preprint* hep-ph/9810221
[15] Barberis D *et al* 1999 *Phys. Lett.* B **467** 165
Close F E and Schuler G 1999 *Phys. Lett.* B **458** 127
[16] Ellis J R and Kharzeev D 1998 *Preprint* hep-ph/9811222
[17] Kochelev N I 1999 *Preprint* hep-ph/9902203
[18] Chung S U, Weygand D P and Willutzki H J 2002 *Preprint* BNL-QGS-02-91 (unpublished)
Kirk A and Villalobos Baillie O 1998 ALICE Note 98/45
Streng K H 1986 *Phys. Lett.* B **166** 443
[19] Adloff C *et al* (H1 Collaboration) 1997 *Z. Phys.* C **76** 613
[20] Adloff C *et al* (H1 Collaboration) 2001 *Eur. Phys. J.* C **20** 29
[21] Affolder T *et al* (CDF Collaboration) 2000 *Phys. Rev. Lett.* **84** 5043
[22] Bunce G, Saito N, Soffer J and Vogelsang W 2000 *Annu. Rev. Nucl. Part. Sci.* **50** 525
[23] Finley J P *et al* 1986 *Phys. Rev.* D **33** 2528
[24] Adloff C *et al* (H1 Collaboration) 1998 *Eur. Phys. J.* C **5** 439
[25] Abachi S *et al* (D0 Collaboration) 1996 *Phys. Rev. Lett.* **76** 734
[26] Hübner B *et al* 1996 STAR Note 276
[27] Abe F *et al* (CDF Collaboration) 1997 *Phys. Rev. Lett.* **78** 2698
[28] Derevschikov A A *et al* 1994 *Preprint* ANL-HEP-CP-95-10
[29] McLerran L 2001 *Preprint* hep-ph/0104285
Gelis F and Peshier A 2002 *Nucl. Phys.* A **697** 879
[30] Baur G, Hencken K, Trautmann D, Sadovsky S and Kharlov Y 2002 *Phys. Rep.* **364** 359
Krauss F, Greiner M and Soff G 1997 *Prog. Part. Nucl. Phys* **39** 503
[31] Klein S and Nystrand J 1999 *Phys. Rev.* C **60** 014903
Klein S and Nystrand J 2000 *Phys. Rev. Lett.* **84** 2330
[32] Adler C *et al* (STAR Collaboration) 2002 *Preprint* nucl-ex/0206004
[33] Klein S, Nystrand J and Vogt R 2002 *Preprint* hep-ph/0206220
[34] Frankfurt L, Strikman M and Zhalov M 2002 *Phys. Lett.* B **540** 220